Mine Burial in Cohesive Sediments: Undrained Shear Strength Characterization

PI: Dr. Charles Aubeny
Civil Engineering Department
Texas A&M University
College Station, TX 77843
phone (979)845-4478, fax (979)845-6554, e-mail Caubeny@civilmail.tamu.edu

LONG TERM GOALS

A critical parameter in mine countermeasure (MCM) planning is the degree of mine impact burial in soft clay or silt seafloor sediments, the degree of burial being largely influenced by the shear strength of the sediments. Previously developed impact burial models show sediment shear strength to be a critical input parameter influencing the degree of embedment. The long term goal of this research is to develop a reliable means for estimating the sediment shear strength for input into mine impact burial models.

OBJECTIVES

While qualitative estimates of sediment shear strength are possible based on correlations to index properties such as grain size or water content, direct measurements will likely provide the most reliable basis for assessing sediment shear strength. Within the context of MCM operations, impact penetrometers provide a promising means of obtaining direct estimates of sediment shear strength. In contrast to more conventional strength measurement methods such as the static cone penetrometer and the field vane, impact penetrometers have the advantage that they can be deployed from a moving vessel and are therefore more adaptable to MCM operations. However, relating dynamic penetration measurements to sediment shear strength involves considerable additional complexity over static measurements. The objectives of this research are to develop an analytical framework for estimating sediment shear strength from dynamic penetration measurements and to calibrate the model to actual field measurements. The framework described herein is specifically applicable to devices such as the expendable bottom penetrometer (XBP, Figure 1) which free falls through a water column and penetrates into seafloor sediments, during which time decelerations are measured from which sediment shear strength may be inferred. Typical impact velocity is on the order of 690 cm/sec.
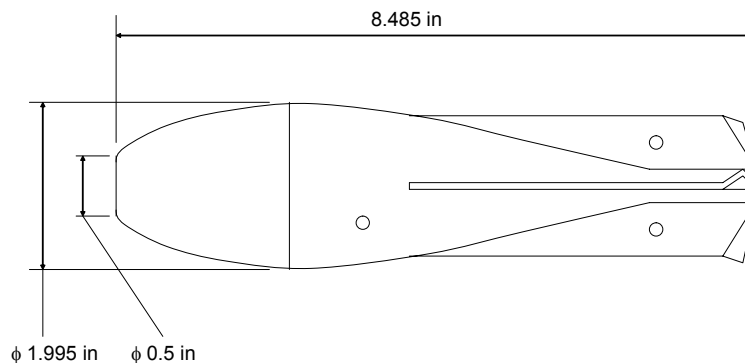

Figure 1. Schematic of Expendable Bottom Penetrometer, XBP (not to scale).

1. REPORT DATE **30 SEP 2004**	2. REPORT TYPE	3. DATES COVERED **00-00-2004 to 00-00-2004**
4. TITLE AND SUBTITLE **Mine Burial in Cohesive Sediments: Undrained Shear Strength Characterization**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Civil Engineering Department,,Texas A&M University,,College Station,,TX,77843**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

APPROACH

The research approach involves three steps:

1. Determination of the relationship between sediment shear strength S_{u0} and the sediment resisting force F_s acting on the penetrometer. This is formulated in terms of a classical bearing capacity equation:

$$F_s = N_c \, S_{u0} \, A \qquad \text{(Eq. 1)}$$

where A is the maximum cross-sectional area of the penetrometer, and N_c is a bearing factor that will be discussed subsequently. It should be noted that the sediment shearing resistance S_u is not unique, but depends on the rate of straining. S_{u0} corresponds to a reference strength corresponding to an arbitrarily specified reference strain rate.

2. Developing a single particle kinetic model to predict acceleration time histories and embedment depths of an impacting penetrometer. The acceleration a of the penetrometer is expressed in terms of the sediment resisting force F_s, a buoyancy force F_b, and the weight W of the penetrometer:

$$a/g = 1 - F_s/W - F_b/W \qquad \text{(Eq. 2)}$$

where g is gravitational acceleration. With acceleration thus defined, other quantities of interest such as velocity v or penetration depth h are readily computed through direct integration.

3. Calibrating the model through comparisons to field measurements.

The tip resistance factor in Step 1 is evaluated using two analytical approaches: the finite element method (FEM) and the strain path method (SPM). The former is a well-established method for analyzing mechanics problems involving complex boundary conditions. The SPM takes advantage of the fact that penetration problems are largely strain-controlled, allowing simplified computational algorithms. The parallel approach utilized in this research facilitates evaluation of computed predictions, so results may be used with greater confidence.

The shearing resistance of clays and silts is dependent on the rate of straining, with higher shearing resistance occurring at elevated strain rates. In instances where the penetration velocity is constant, the conventional cone penetration test being an example, correcting for strain rate effects is somewhat simpler, since a single correction factor can be applied to penetration resistance predictions. However, impact penetration entails variable velocity conditions, ranging from high values at impact to zero velocity at final embedment. Hence, the shear strength of the sediment varies continuously throughout the penetration process. To account for this effect, the finite element studies used in this research employed a strain rate dependent plasticity material model so that end bearing factors may be calculated as a function of penetration velocity, v. Similarly, SPM algorithms were modified to model the dependence of clay and silt strength on strain rate.

Aside from strain rate, several other factors affect the tip resistance factor relating sediment shear strength to the resisting force acting on the penetrometer. These include:

- Depth of penetrometer embedment, *h*. At shallow embedments, the tip resistance factor is considerably lower than that at greater depths due to the proximity of a free surface.

- Adhesion factor between the sediment and the penetrometer, α. The degree to which the sediment adheres to the advancing penetrometer will also affect the tip resistance factor. This effect can be characterized in terms of an adhesion factor α, defined as the ratio of the shearing resistance mobilized on the boundary of the penetrometer to the shearing strength of the sediment. A first approximation, α may be taken as the ratio of remolded to intact strength of the sediment.

From the FEM and SPM analyses discussed earlier, the tip resistance factor can be expressed as a function of penetration velocity, embedment, and adhesion:

$$N_c = f \text{ (velocity } v \text{, embedment depth } h \text{, adhesion } \alpha) \qquad \text{(Eq. 3)}$$

With Eq. 3 defined, a model of impact penetration can be directly formulated from the equations of motion of a single particle. From this model, relationships between penetrometer deceleration and sediment shear strength can be developed for various conditions of impact velocity and sediment sensitivity. These relationships provide the basis for inferring sediment shear strength from penetrometer (e.g., XBP) deceleration measurements.

WORK COMPLETED

Evaluation of the bearing factor N_c (Eq. 3) using finite element analyses supplemented by strain path analyses has been completed. Incorporation of N_c into a MATLAB algorithm for computing the sediment resisting force (Eq. 1) and XBP deceleration profiles (Eq. 2) has also been completed.

RESULTS

Computed N_c values for velocities 0- 3500 cm/sec and penetration depths 0-36 cm are shown in Figure 2. This figure provides the basis for computing the sediment resisting force F_s (Eq. 1) and XBP decelerations during penetration into the seafloor (Eq. 2). These computations provide the basis for estimating seafloor sediment strength from XBP measurements. Several approaches are possible.

Figure 3 shows one possible correlation, XBP decelerations versus sediment shear strength S_{u0}. Figure 4 shows an alternative approach, XBP penetration depth versus sediment strength.
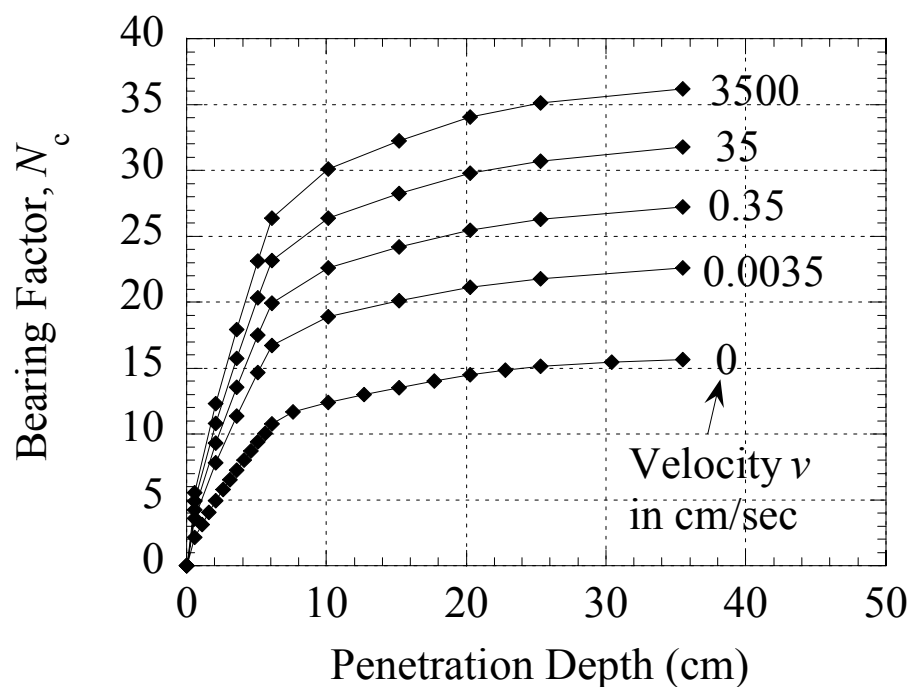
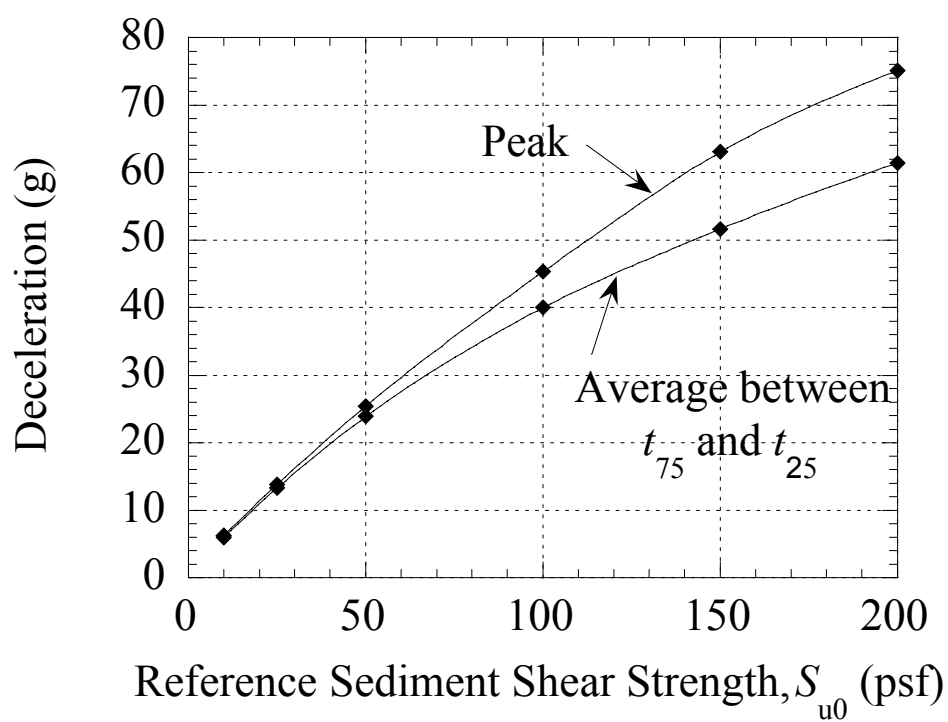*Figure 2. XBP Bearing Factor versus Velocity and Penetration Depth*

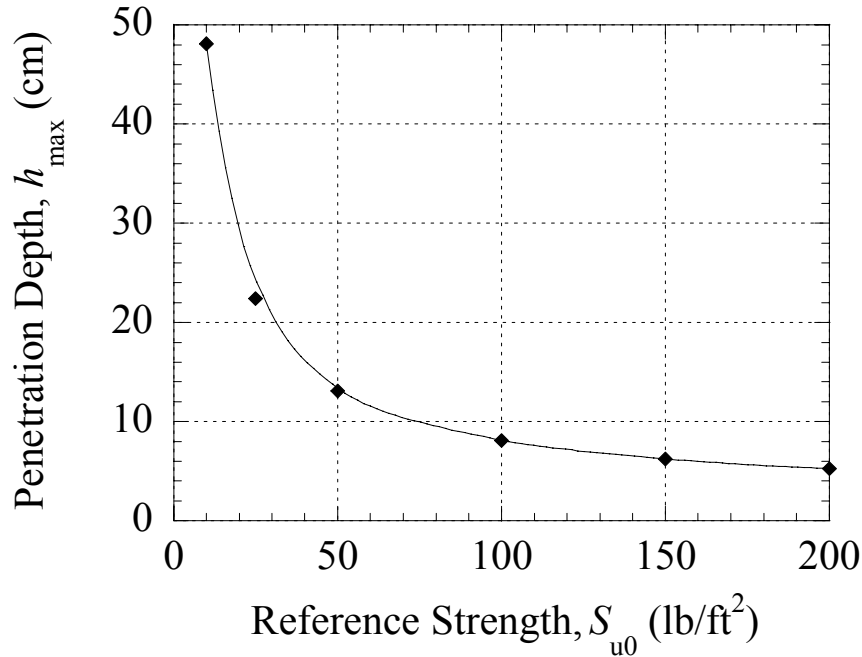*Figure 3. XBP Deceleration versus Sediment Strength*

Figure 4. XBP Penetration Depth versus Sediment Strength

IMPACT/APPLICATIONS

Correlations such as those illustrated in Figures 3 and 4 provide a direct basis for estimating the appropriate sediment shear strength to be input in mine impact burial prediction models.

In principle, any XBP measurement – penetration depth, velocity, or acceleration – should correlate to sediment strength. However, practical considerations may demonstrate one approach to be preferable over another; possible approaches include:

• *Peak decelerations* measured during penetration (Figure 3) are likely to be sensitive to local non-homogeneities in the sediment profile and may not necessarily represent the average strength characteristics over the depth of interest.

• *XBP penetration* depth (Figure 4) will likely present a better measure of average strength over the depth of interest. However, measurement of penetration depth can require fairly precise determination of exactly when the XBP touches the seafloor, which may be difficult in soft seafloor conditions.

• *Average deceleration* over a specified time interval, say in the 25 and 75 percent time interval (Figure 3), can provide an attractive basis for estimating sediment strength from XBP measurements. This approach has the advantage that it is representative of sediment conditions over a fairly wide portion of the XBP penetration depth, but does not require accurate estimates of exactly when the penetrometer touches down on the seafloor.

TRANSITIONS

Studies are still in progress regarding selection of the most robust approach for interpreting XBP measurements. Upon completion of these studies, recommended guidelines for estimating sediment shear strength from XBP measurements can be made available to users of mine impact burial prediction models.

RELATED PROJECTS

This project directly follows from a previous project by the PI "Experimental and Analytical Investigation of Mine Burial Penetration." As sediment shear strength is a basic input into mine impact burial penetration models, this project is also directly relevant to the instrumented mine drop experiments conducted by NRL and their studies on the validity of IMPACT28 and other mine impact burial programs under consideration.